



Validation of premixed combustion models using turbulent Bunsen flames at high pressure

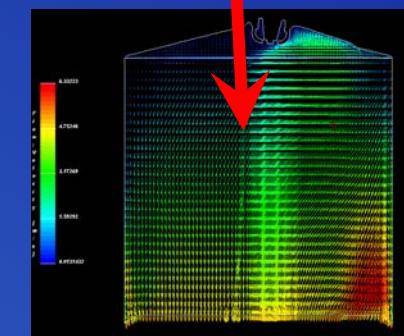
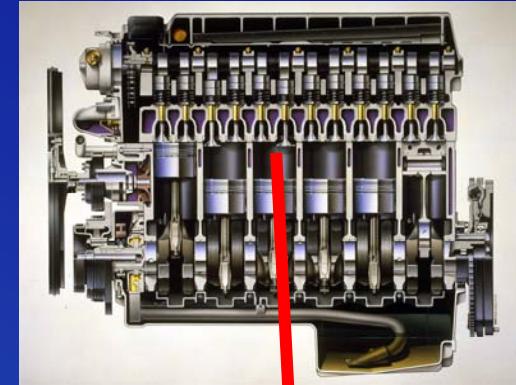
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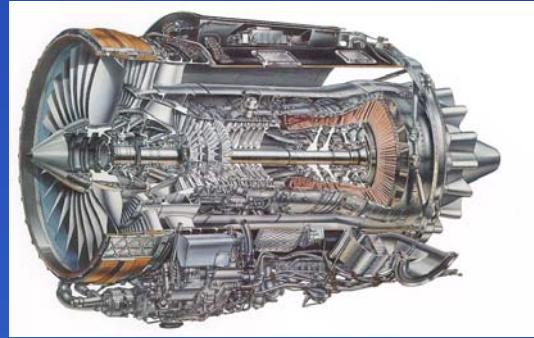


1. Introduction
2. Turbulent premixed combustion model
3. Kobayashi validation case
4. Validation CFD calculations
5. Conclusions

- Partially premixed flames in applications
- Varying pressure, (unburnt) temperature, Φ
- Partially premixed model includes premixed case
- Need for validation data
- Need for CFD validation calculations



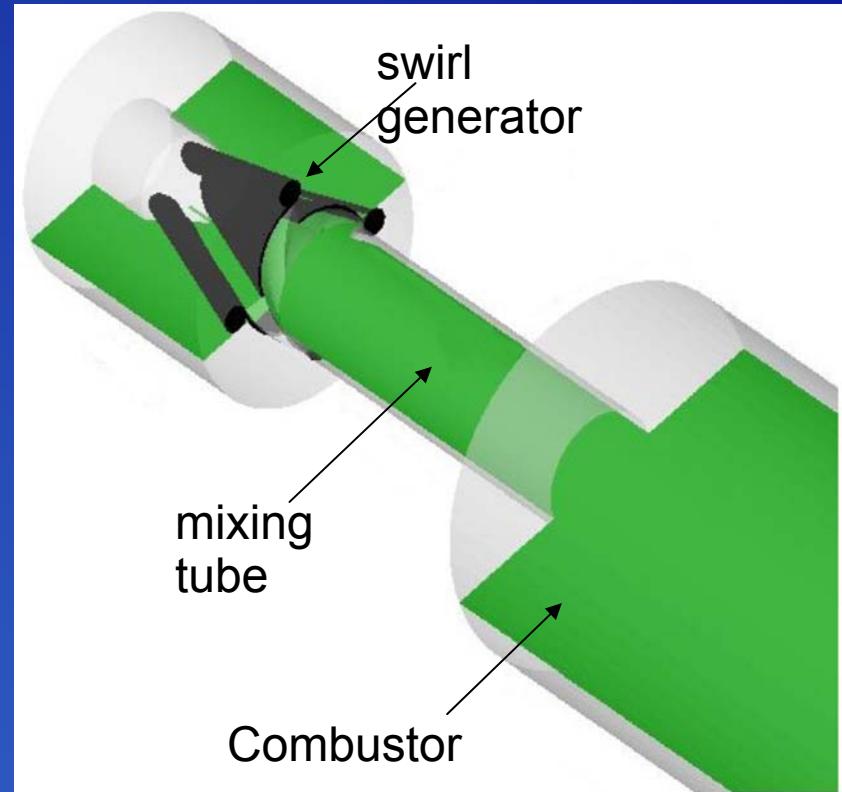
Motivation



CFD-Codes:

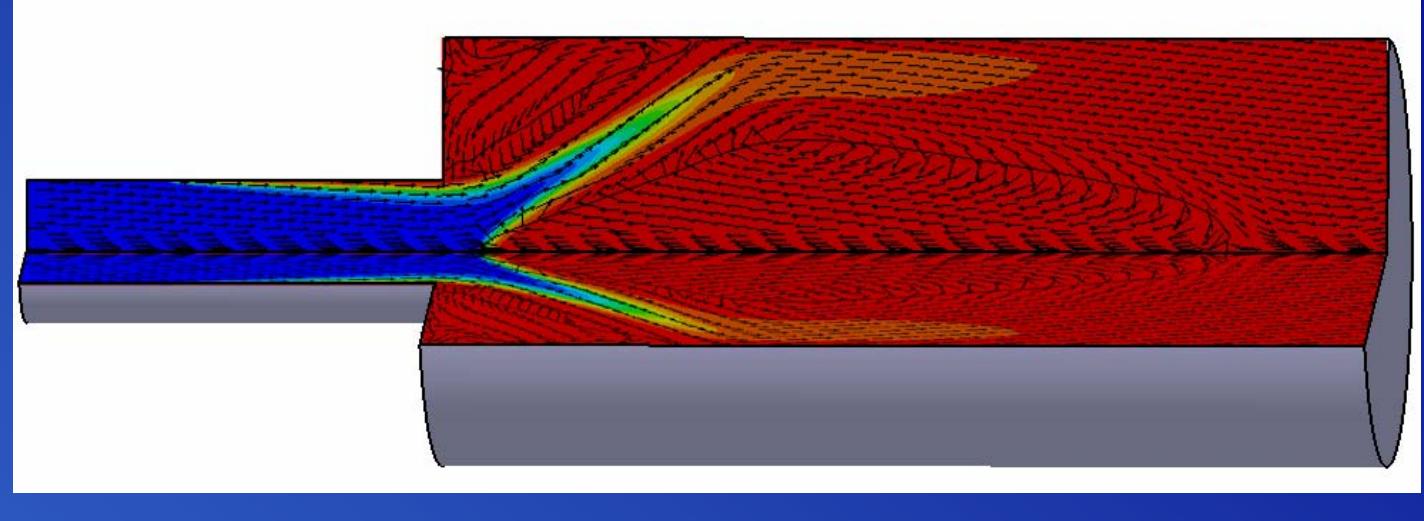
1) FLUENT (RANS - URANS)
stationary / unsteady

2) LES-Code (Janicka)
unsteady

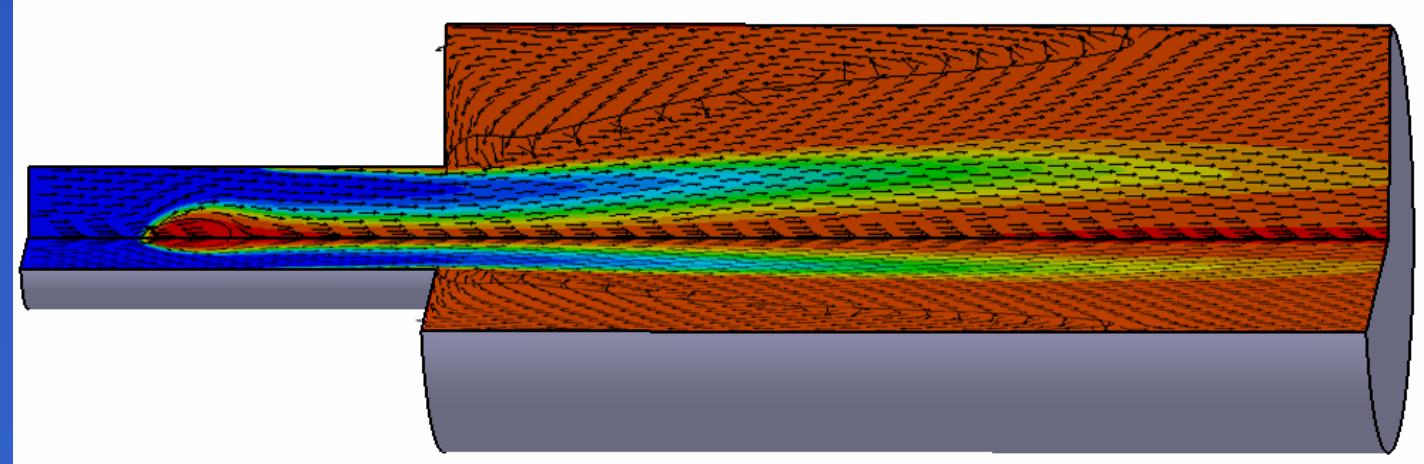


Simulation of flashback into mixing tube

stable operation



flash back



Combustion induced vortex breakdown



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Favre-averaged Conservation Equations

Mass:

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial (\bar{\rho} \tilde{u}_i)}{\partial x_i} = 0$$

Momentum:

$$\frac{\partial}{\partial t}(\bar{\rho} \tilde{u}_i) + \frac{\partial}{\partial x_j}(\bar{\rho} \tilde{u}_i \tilde{u}_j) = \bar{\rho} g_i - \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial \bar{\tau}_{ij}}{\partial x_j} - \frac{\partial}{\partial x_j}(\bar{\rho} \widetilde{\tilde{u}_i \tilde{u}_j})$$

Species:

$$\frac{\partial}{\partial t}(\bar{\rho} \tilde{Y}_\alpha) + \frac{\partial}{\partial x_i}(\bar{\rho} \tilde{u}_i \tilde{Y}_\alpha) = \frac{\partial}{\partial x_i} \left(\bar{\rho} D_\alpha \frac{\partial \tilde{Y}_\alpha}{\partial x_i} \right) - \frac{\partial}{\partial x_i} \bar{\rho} \widetilde{\tilde{u}_i \tilde{Y}_\alpha} + \tilde{R}_\alpha$$

Enthalpy:

$$\frac{\partial}{\partial t}(\bar{\rho} \tilde{h}) + \frac{\partial}{\partial x_i}(\bar{\rho} \tilde{u}_i \tilde{h}) = \frac{\partial}{\partial x_i} \left(\bar{\rho} D_h \frac{\partial \tilde{h}}{\partial x_i} \right) - \frac{\partial}{\partial x_i} \bar{\rho} \widetilde{\tilde{u}_i \tilde{h}} + \dot{q}_{str}$$

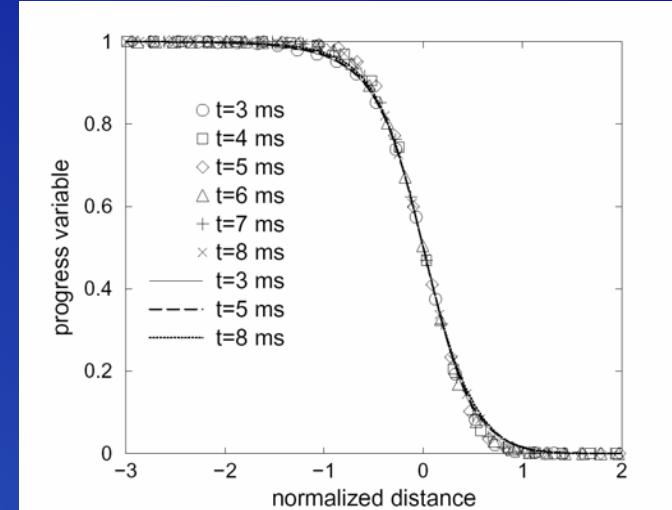
→ unclosed Terms need modelling, reaction source term very nonlinear:

$$\tilde{R}_\alpha \neq f(\tilde{c}_i, \tilde{T})$$



OH visualisation flame front

Transport equation for Favre-averaged progress variable:



Reaction progress turbulent premixed flame

$$\frac{\partial}{\partial t}(\bar{\rho}\tilde{c}) + \frac{\partial}{\partial x_i}(\bar{\rho}\tilde{u}_i\tilde{c}) = -\frac{\partial}{\partial x_i}\left(\bar{\rho}\widetilde{u_i'c'}\right) + \bar{S}_c$$

Constant pressure:

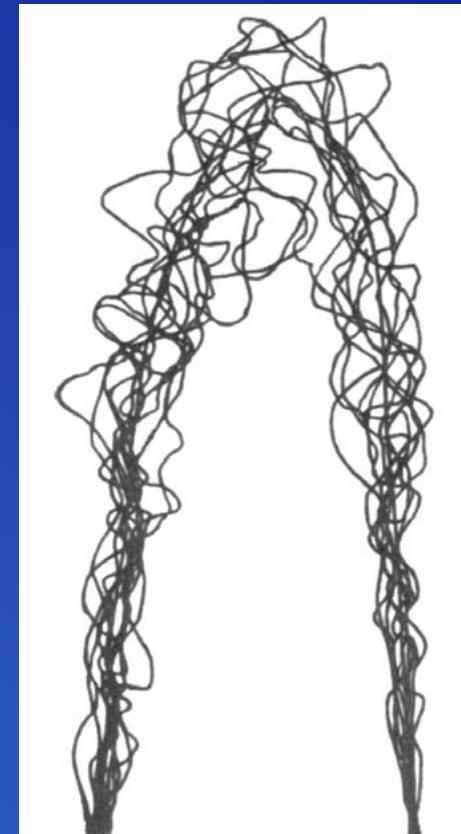
$$\tilde{c} = \frac{\tilde{T} - T_u}{T_b - T_u}$$

Reaction progress variable transport equation

Increase of burning rate through folding of flame



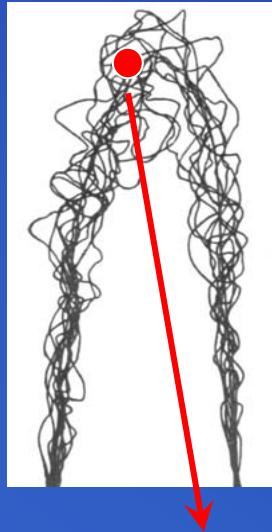
Schlieren picture



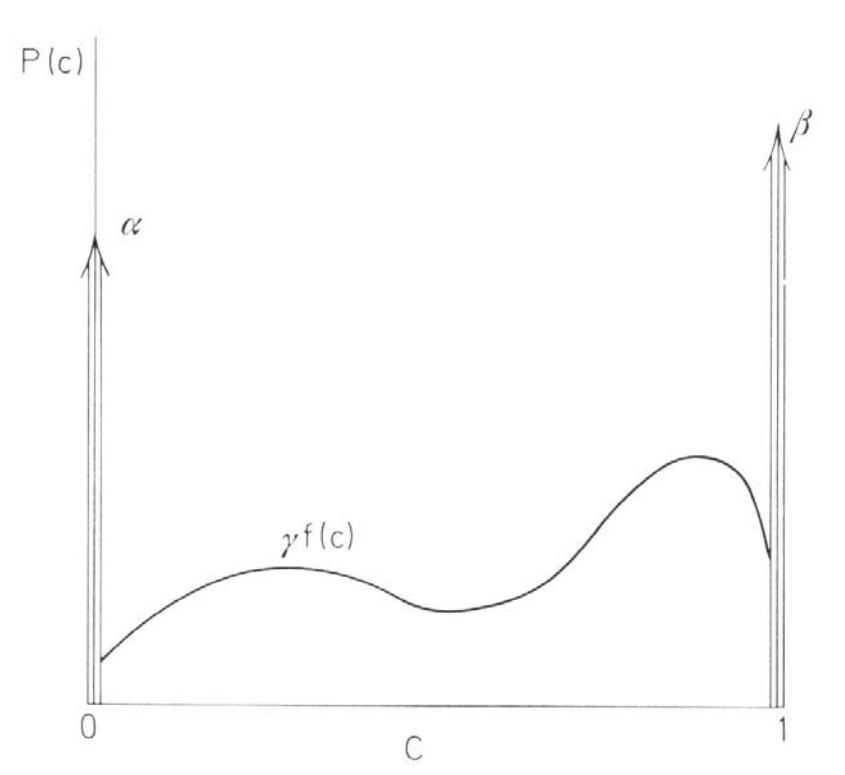
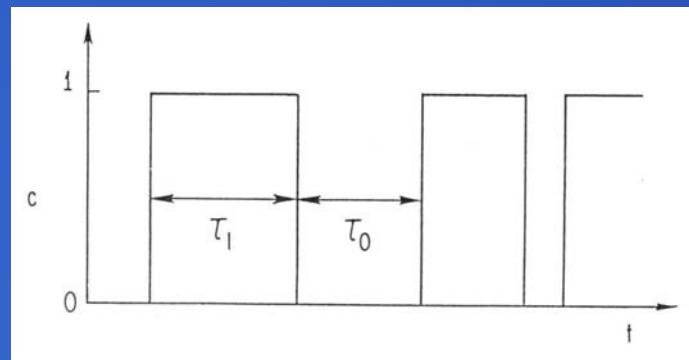
Instantaneous flame front

Flame front of a turbulent Bunsen flame

Probability density function (PDF) for reaction progress $c(x)$

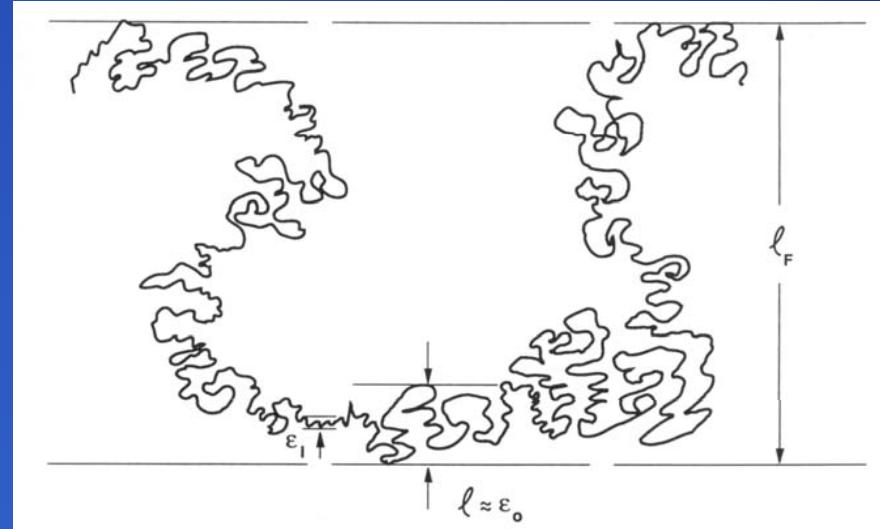


$$c = \frac{T - T_u}{T_b - T_u}$$

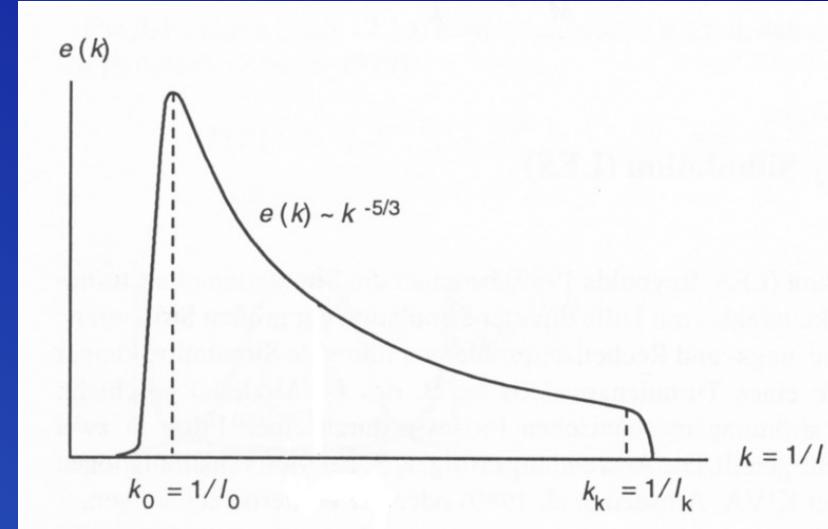


$$\gamma \rightarrow 0 \Rightarrow \tilde{c}''^2 = \tilde{c} \cdot (1 - \tilde{c})$$

Bray-Moss-Libby-Model



fractal flame front



turbulence spectrum

Turbulent burning rate $\overline{S_c} = \rho_u \cdot s_{l,0} \cdot \Sigma$

- ρ_u density of unburnt gases
- $s_{l,0}$ laminar flame speed
- Σ flame surface density Σ from fractal theory [Gouldin1989]:

$$\Rightarrow \overline{S_c} = C_R \cdot \rho_u \cdot \frac{s_{l,0}}{V_k} \cdot \frac{\tilde{\epsilon}}{\tilde{k}} \cdot \tilde{c} \cdot (1 - \tilde{c})$$

Lindstedt-Vaos model

Lindstedt-Vaos model:

$$\bar{S}_c = C_R \cdot \rho_u \cdot \frac{s_{l,0}}{\nu^{1/4}} \cdot \frac{\tilde{\epsilon}^{3/4}}{\tilde{k}} \cdot \tilde{c} \cdot (1 - \tilde{c})$$

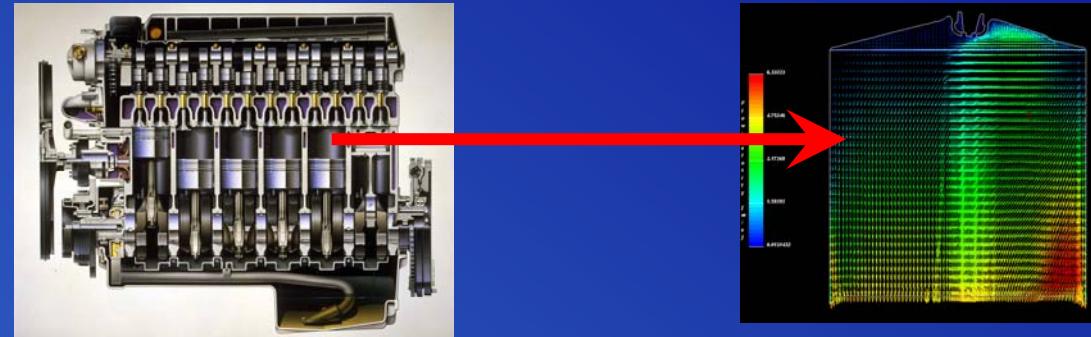
Schmidt model:

$$\bar{S}_c = 4.96 \cdot C_R \cdot \frac{\tilde{\epsilon}}{k} \left(\frac{s_l}{\sqrt{2/3k}} + \left(1 + Da^{-2} \right)^{-1/4} \right)^2 \cdot 4 \cdot \tilde{c} \cdot (1 - \tilde{c}) \cdot \rho_u Y_{f,u}$$

$$Da^{-1} = \frac{4.96}{0.09} \frac{\tilde{\epsilon}}{k} c_0^{w^2} \frac{a_0}{s_l^2}$$

Reaction source terms

ICE application: p , $T_{u,f}$, $T_{u,ox}$ changes during simulation, partial premixing

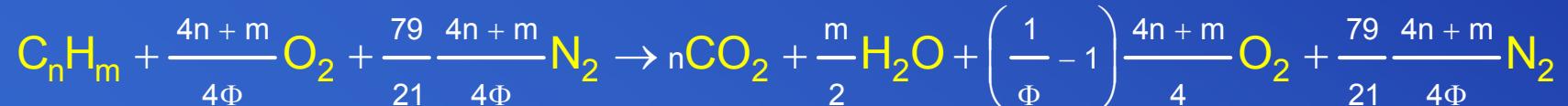


Mass fraction transport
equation:

$$\frac{\partial}{\partial t}(\bar{\rho}\tilde{Y}_i) + \frac{\partial}{\partial x_i}(\bar{\rho}\tilde{u}_i\tilde{Y}_i) = -\frac{\partial}{\partial x_i}\bar{\rho}\widetilde{u_i''Y_i''} + \bar{R}_i$$

$\tilde{c} = \frac{\tilde{Y}_p - Y_u}{Y_b - Y_u}$
 $\bar{R}_i = \bar{S}_c \cdot (Y_b - Y_u)$

1-step global reaction:



Mass fraction transport equation

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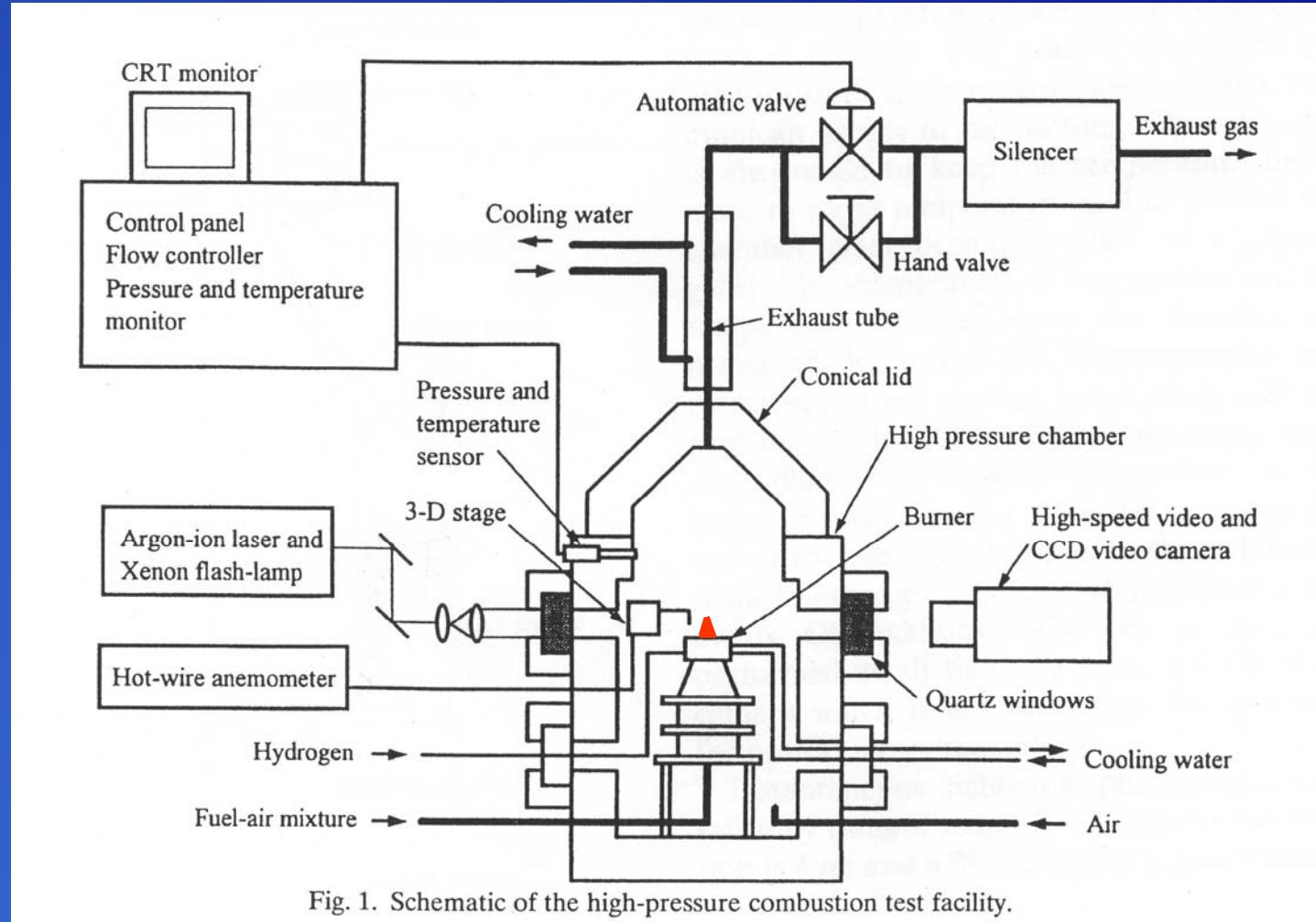
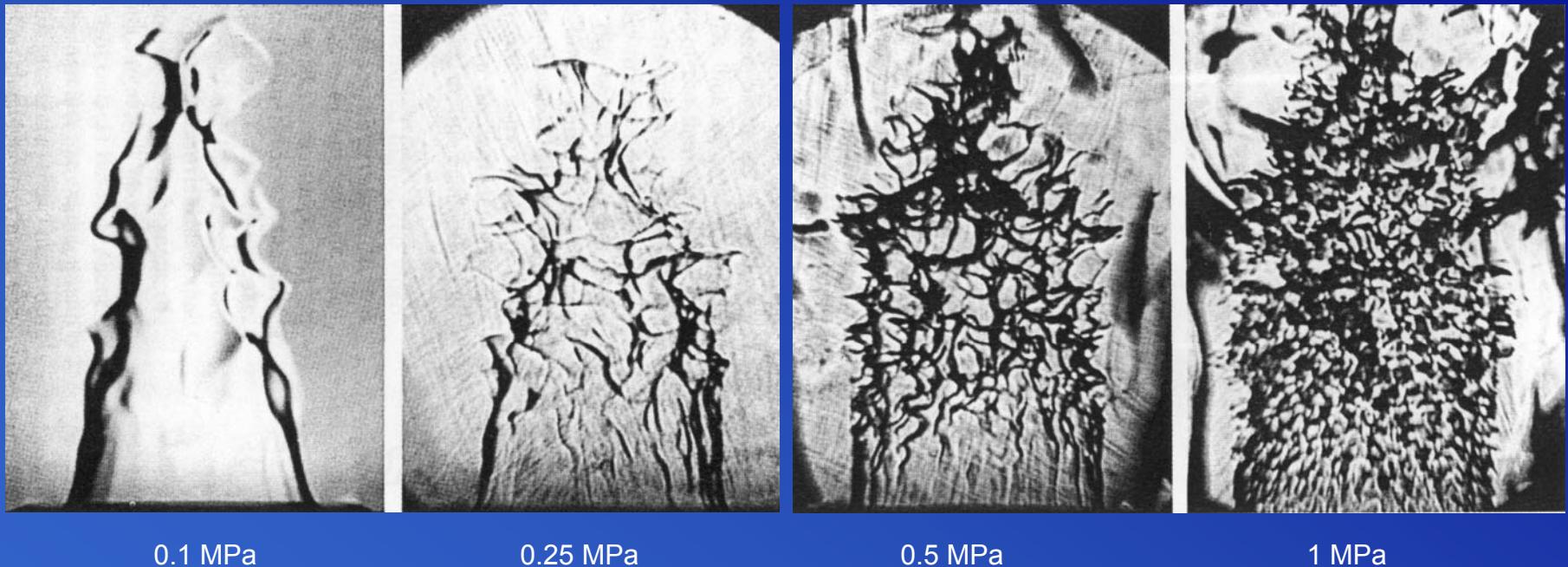


Fig. 1. Schematic of the high-pressure combustion test facility.

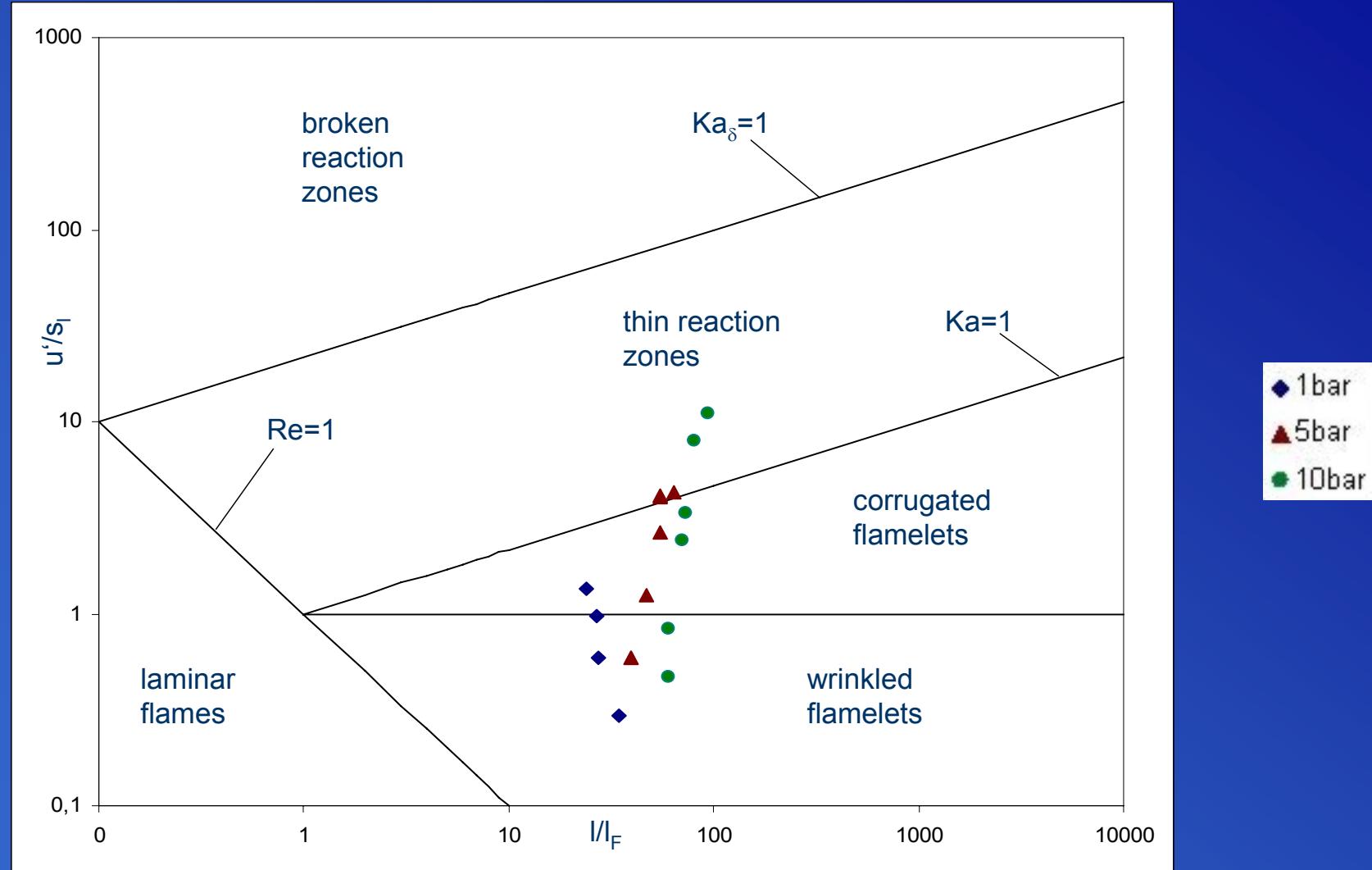
Validation configuration (Kobayashi)



$\Phi=0.9$, $u=2.0\text{m/s}$, $d=20\text{mm}$

$\text{Re} \uparrow$: fractal flame strucutre, flame instabilities (?)

Schlieren pictures at different pressures

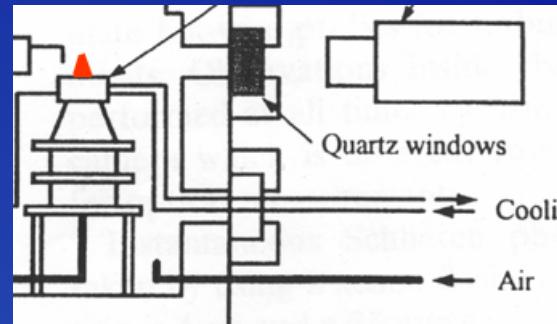


Experimental conditions in regime-diagram

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Two streams – different composition (fuel / air): use Carbon mixture fraction

$$f = \frac{Z_C - Z_{C,o}}{Z_{C,f} - Z_{C,o}}$$



Progress variable including mixing effect:

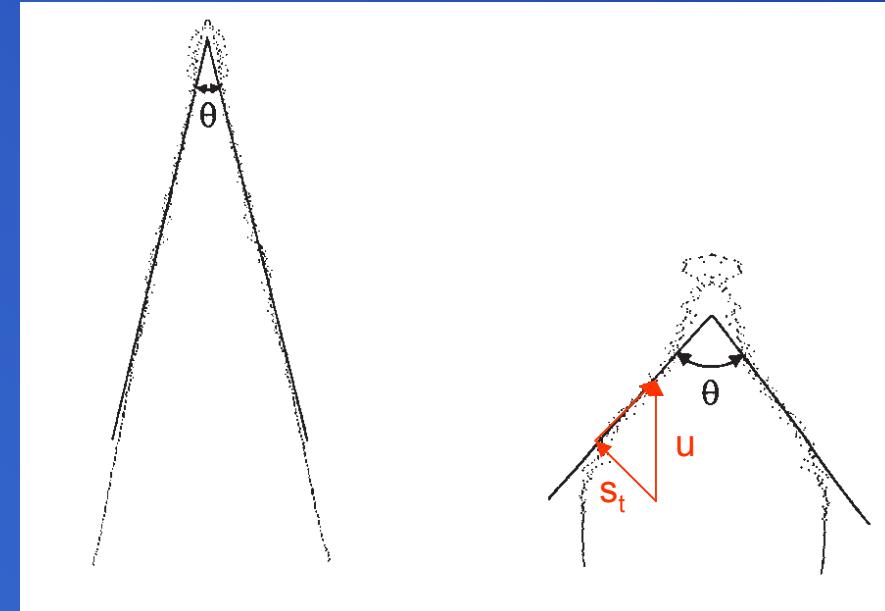
$$\tilde{c} = 1 - \frac{\tilde{Y}_F - f \cdot Y_{F,b}}{(Y_{f,u} - Y_{f,b}) \cdot f}$$

Boundary conditions:

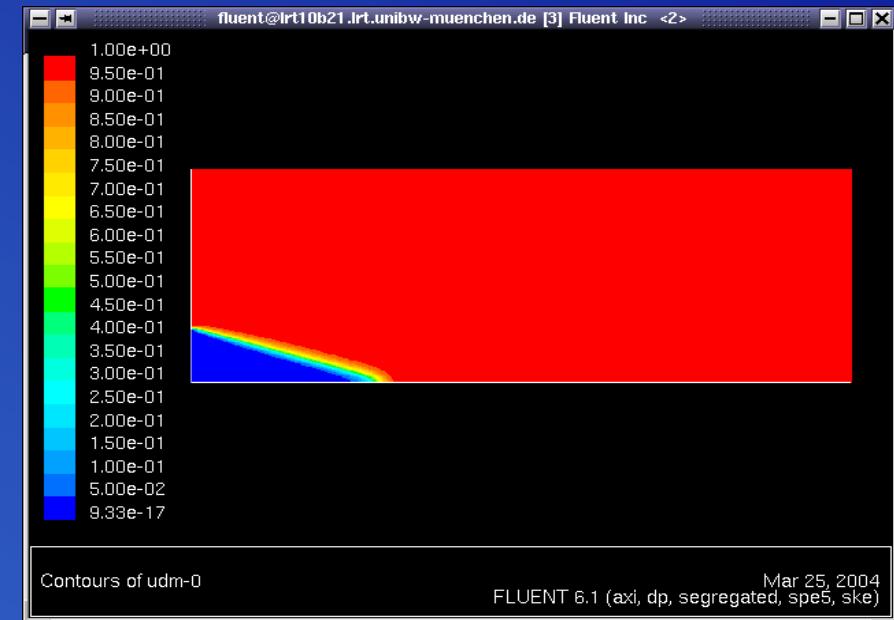
p	1bar, 5bar, 10bar
v_{inlet}	2.02 bis 4.06m/s
v'_{inlet} :	0.09 bis 0.65 m ² /s ²
fuel:	Methane / Air, $\Phi=0.9$
inlet diameter:	20mm

Flame angle from flame conus: $s_t = u \cdot \sin\left(\frac{\theta}{2}\right)$

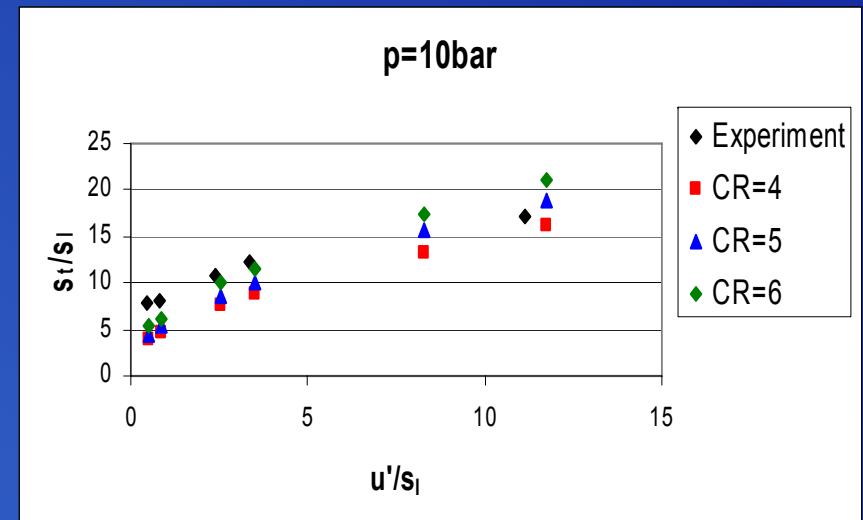
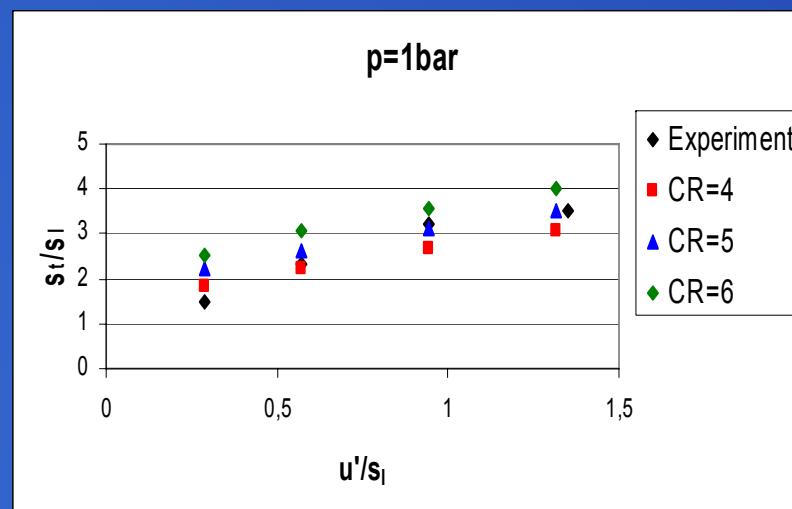
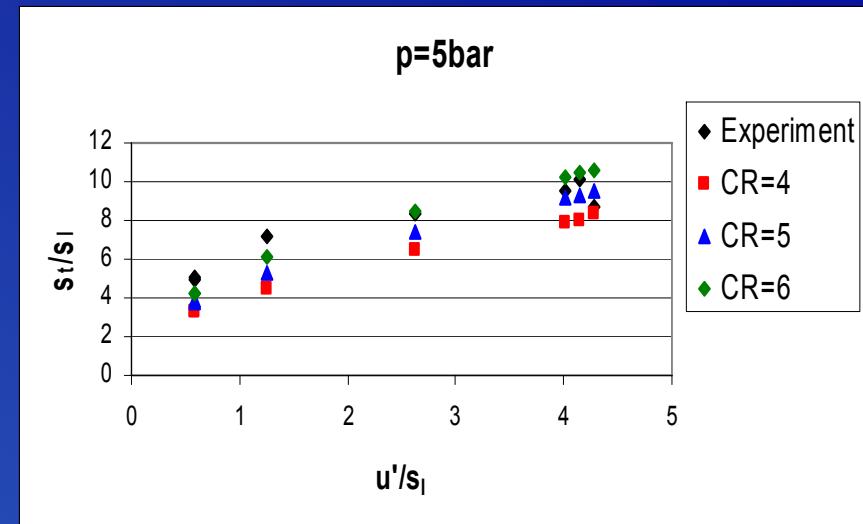
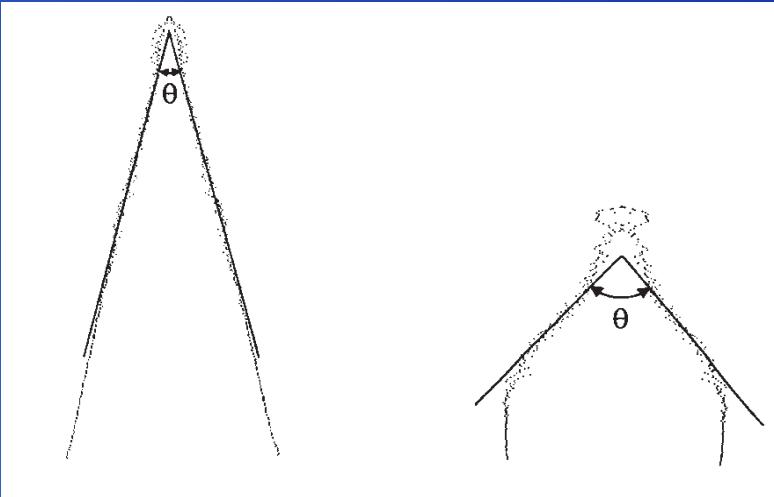
Experiment



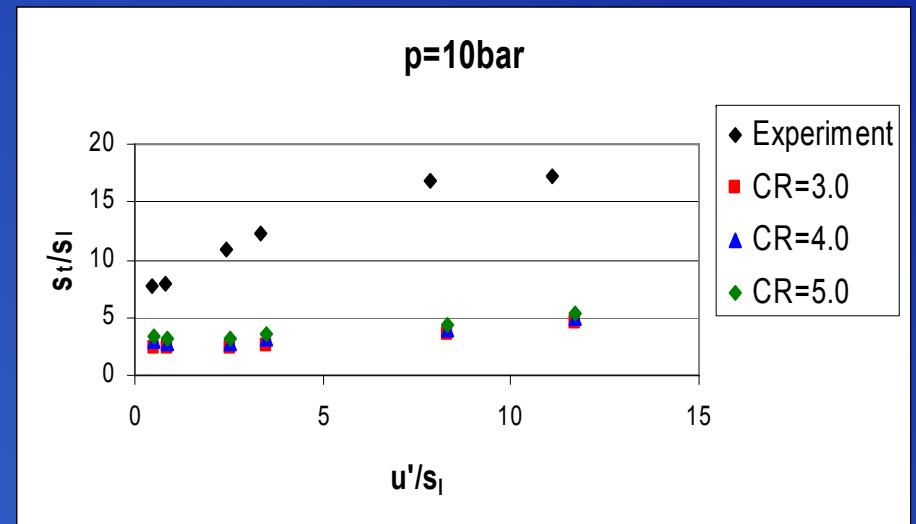
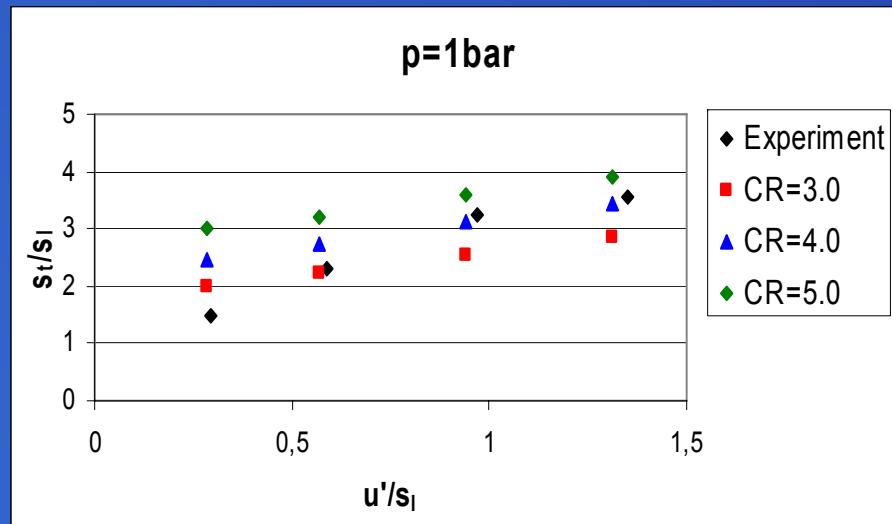
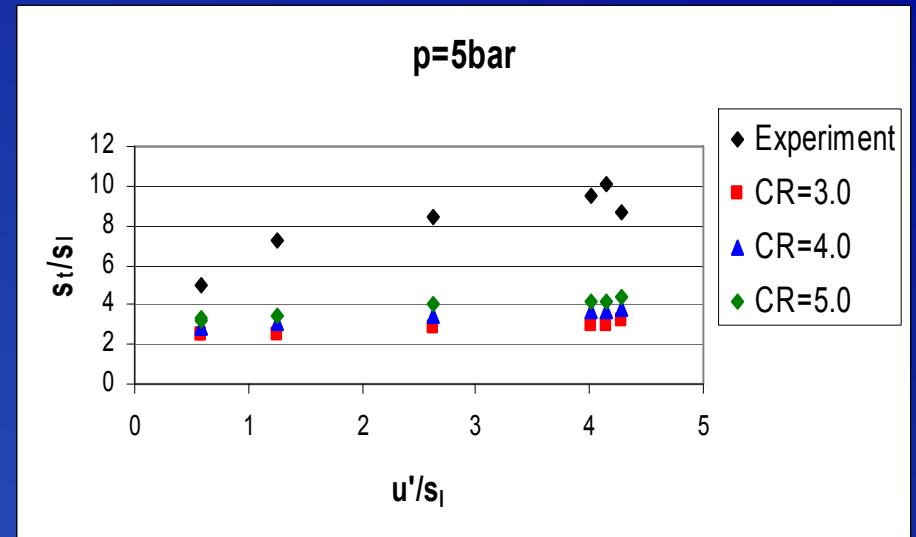
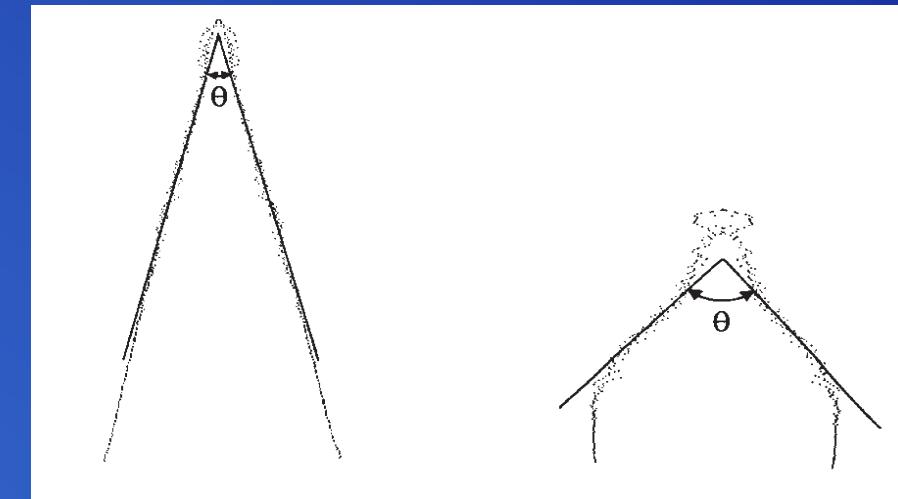
Simulation: $\bar{c} = \frac{(1+\tau)\tilde{c}}{1+\tau\tilde{c}}$



Validation of combustion model using flame cone angle



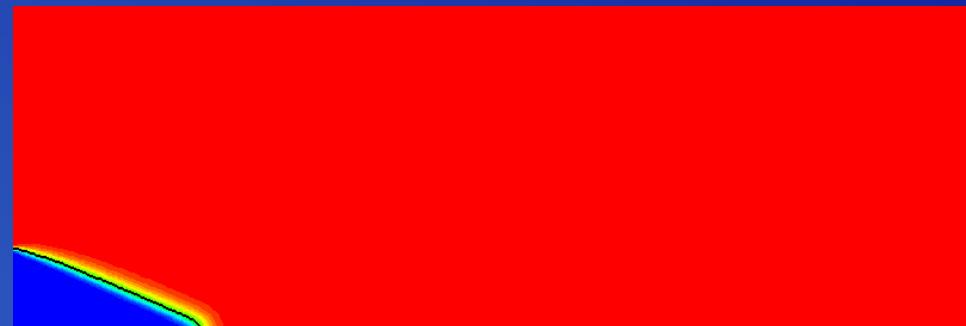
Results with Lindstedt-Vaos-Model (Methane/Air $\Phi=0.9$)



Results with Schmid-Model (Methane/Air $\Phi=0.9$)

- Good agreement between both models for $p=1\text{bar}$.
- Conical flame surface allows to determine the turbulent flame speed.

Lindstedt-Vaos-Model:
 $1\text{bar}, u'/s_l=0.285$



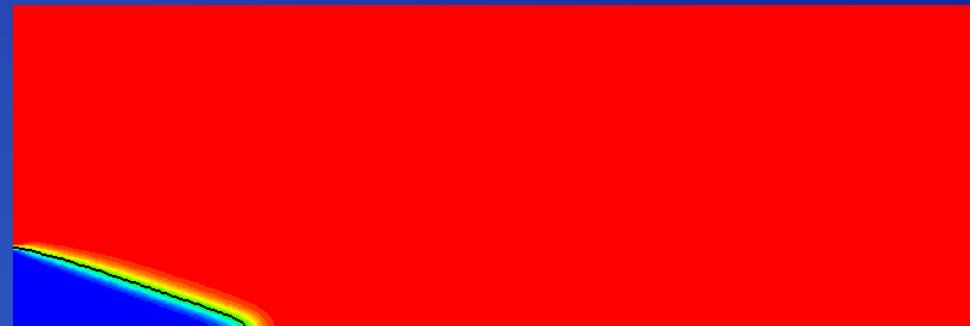
Schmid-Model:
 $1\text{bar}, u'/s_l=0.285$



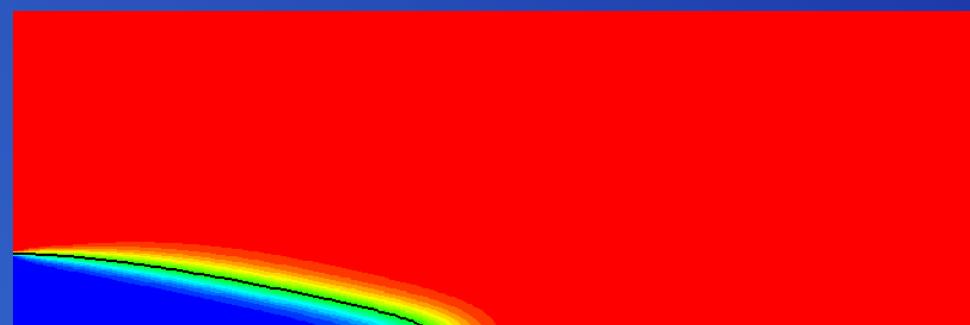
Reaction Progress at 1bar

- Good prediction of the turbulent flame speed by the Lindstedt-Vaos-Model.
- Schmid-Model underestimates the turbulent flame speed at higher pressure.

Lindstedt-Vaos-Model:
5bar, $u'/s_l = 1.25$



Schmid-Model:
5bar, $u'/s_l = 1.25$



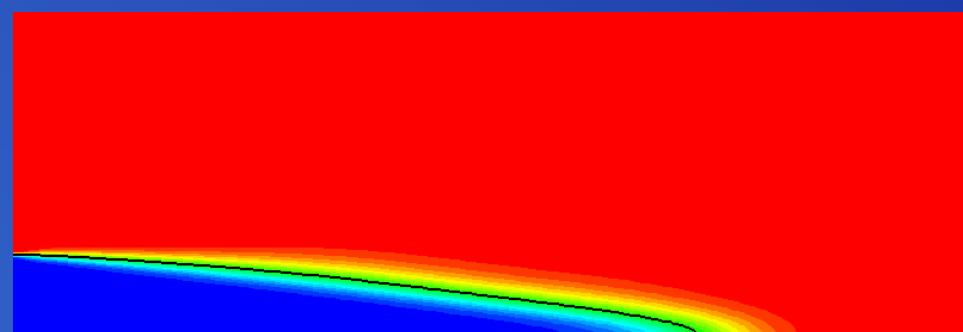
Reaction Progress at 5bar

- Good prediction of the turbulent flame speed by the Lindstedt-Vaos-Model.
- Schmid-Model underestimates the turbulent flame speed at higher pressure.

Lindstedt-Vaos-Model:
10bar, $u'/s_l = 0.88$



Schmid-Model:
10bar, $u'/s_l = 0.88$



Reaction Progress at 10bar

- Require high-accuracy validation data turbulent premixed flames:
 - different (gaseous) fuels, Φ (\rightarrow Le-effect)
 - inflow velocity, turbulence, length scale (\rightarrow different flame regimes)
 - pressure
 - temperature
- Bunsen flame: flame angle + flame form, flame brush
- If possible: species / velocities conditioned to reaction progress

\rightarrow from Experiment and / or DNS ?

\rightarrow can perform „DNS-friendly“ experiment ?

Conclusions (I)

- Extension of turbulent combustion models for
 - Incorporation of low Re-, Le-effects
 - Adaption to temporally varying p , T_u
 - Partial premixing (local Φ variation, fresh air, EGR)
 - Validation for whole range (regime, pressure, temperature, composition)
- Would like **few** flames (series) with high accuracy, **complete** data to further develop theory